



Resolving dynamic ground motions with high-rate GNSS and implications for data fusion in broadband seismology and Earthquake Early Warning

EGU General Assembly 2020

Roland Hohensinn¹, Nikolaj Dahmen², John Clinton³, Alain Geiger¹, Markus Rothacher¹

¹Institute of Geodesy and Photogrammetry, ETH Zurich; ²Institute of Geophysics, ETH Zurich; ³Swiss Seismological Service (SED)

Resolving Hazardous Ground Movements with GNSS



Autonomous GNSS station

(Image: P. Limpach)

Geodetic GNSS can resolve ground movements ranging from *Millimeters per Year* to *Millimeters per Second*

Long-term monitoring (mm level)

Commonly based on static GNSS with daily resolution
Tectonics, post-glacial rebound, slope monitoring, ...

Short-term monitoring (cm to mm level)

Real-time kinematic methods (RTK, PPP, velocity estimation), up to 100 Hz resolution

Seismic monitoring, structural health monitoring, landslide monitoring ...

How small can dynamic movements be in order to be detected?

Detection of Significant Displacements

- **Basis: epoch-wise estimation of displacement parameters $\hat{\mathbf{x}}$**

Under a null hypothesis $H_0 : E(\hat{\mathbf{x}}) = 0$ (no movement) the test quantities are

... in case the variance of the parameters is known:

$$\hat{\mathbf{x}}^T \Sigma_{\hat{\mathbf{x}}\hat{\mathbf{x}}}^{-1} \hat{\mathbf{x}} \sim \chi^2(f, 0)$$

... in case the variance of the parameters is estimated

$$\hat{\mathbf{x}}^T \mathbf{S}_{\hat{\mathbf{x}}\hat{\mathbf{x}}}^{-1} \hat{\mathbf{x}} \sim F(f, r, 0)$$

- Given the variance and non-centrality parameters, *minimum detectable displacements* can be computed

Seismic Monitoring with GNSS Instantaneous Velocity Estimates

Instantaneous Velocity Estimates:

- Based on time-differenced carrier phase
- Real-time, high-rate (≥ 1 Hz), stand-alone
- Detection down to sub-mm/s possible

Hohensinn R. et al, «*Movement Detection Based on High-Precision Estimates of Instantaneous GNSS Station Velocity.*», Surveying Engineering, 2019

Example:

- Italian „RING“ GNSS network (RHS)
- M_w 6.5 earthquake in 2016 „Norcia“
- Station distance from epicenter:
Few km up to ~180 km

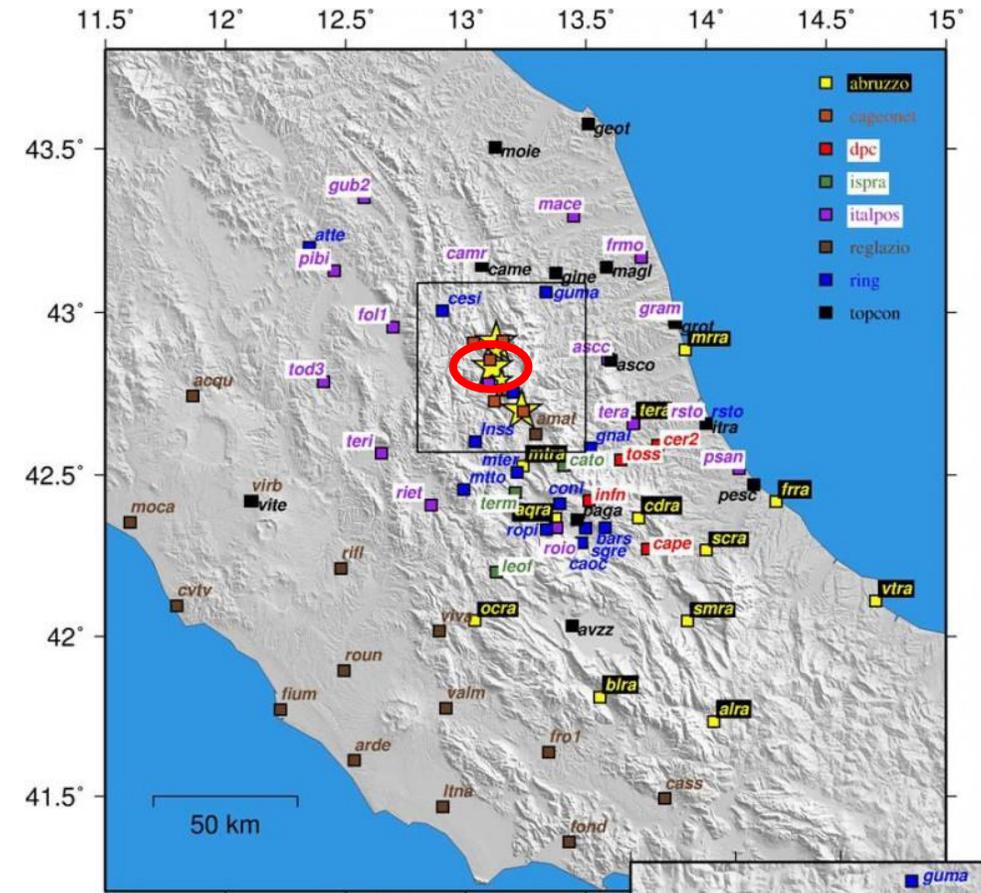
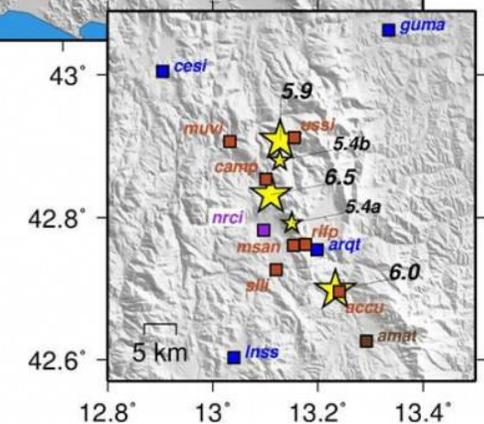


Image Source:
ring.gm.ingv.it/?p=1333



Norcia Earthquake: Results

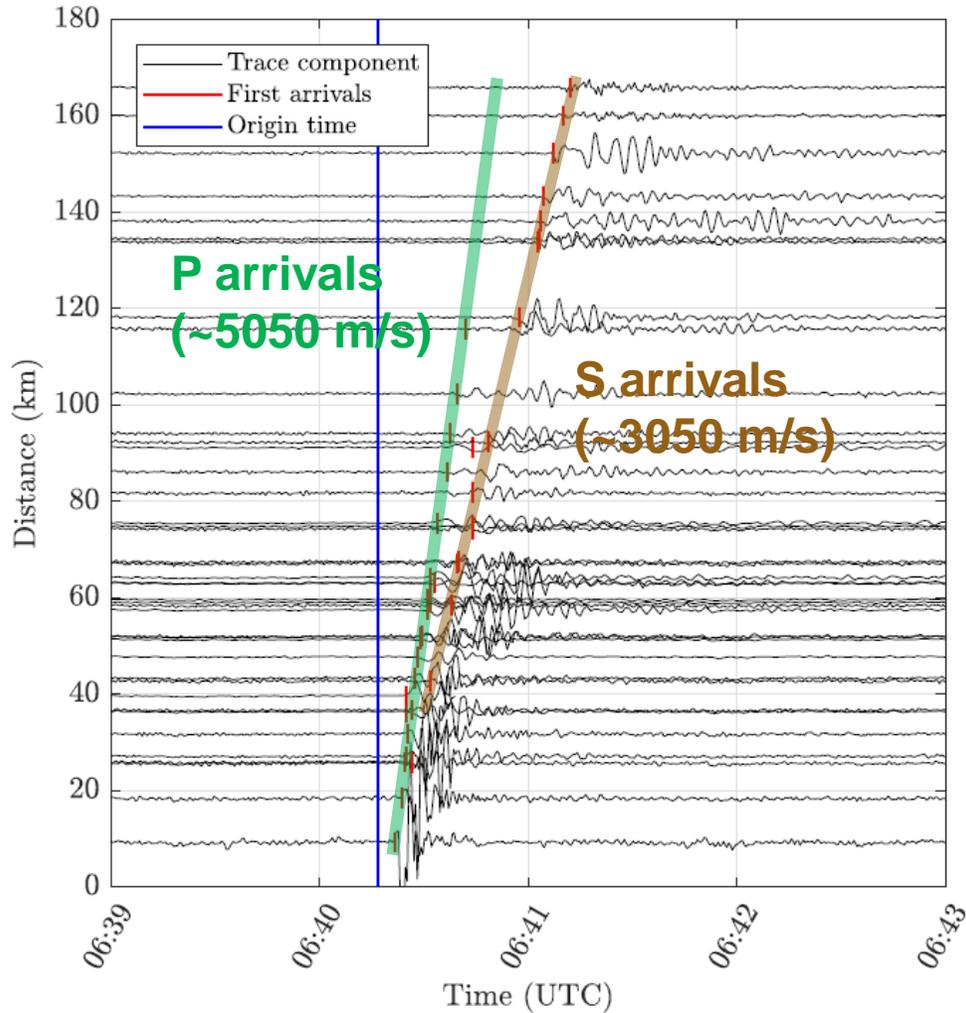
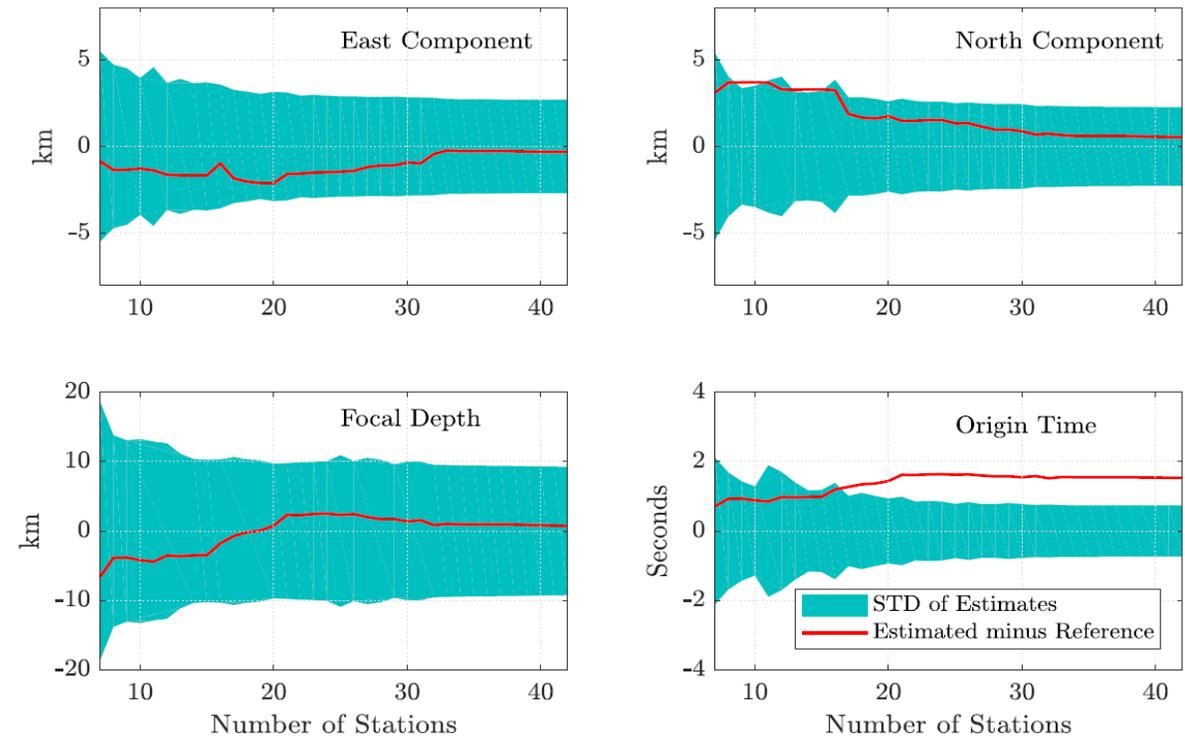


Figure (left): GNSS Velocity north component and detected first arrivals

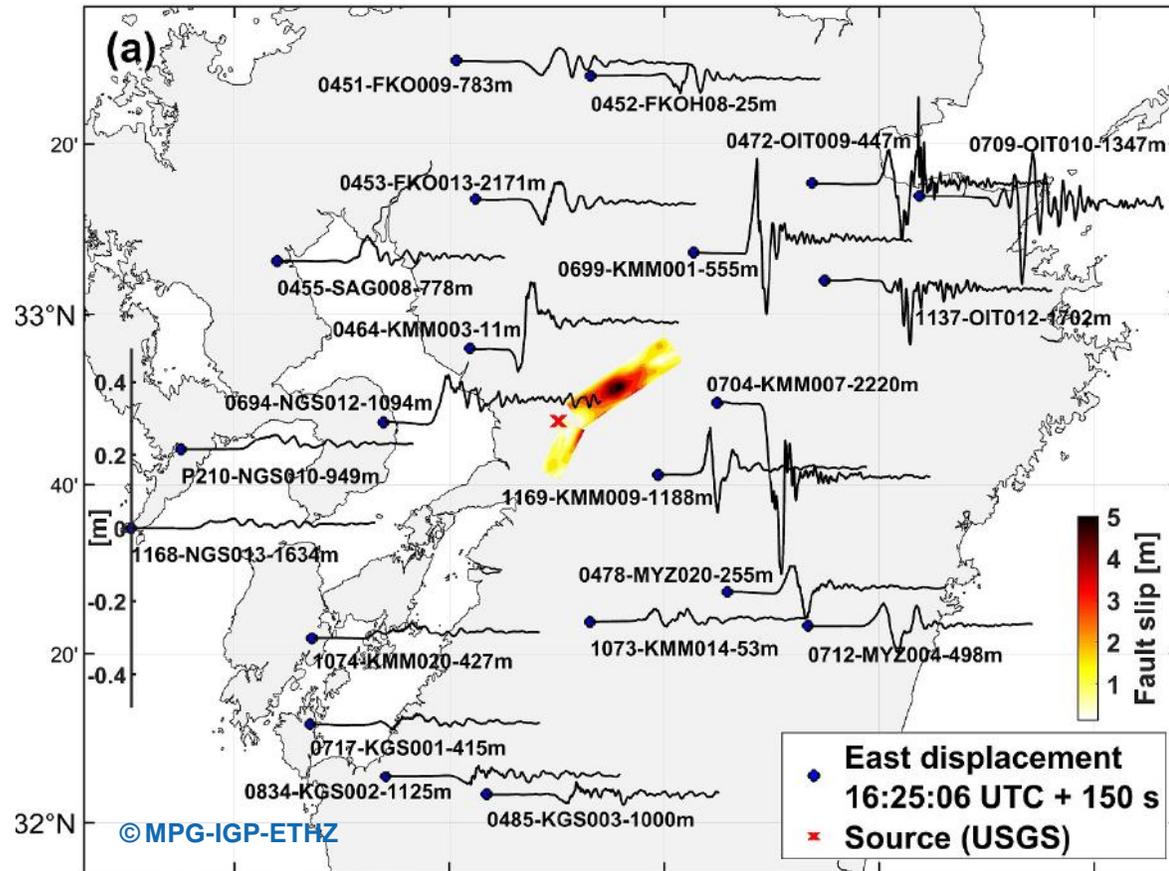
Figure (bottom): Results from GNSS-only hypocenter localization



... as close as 1 km to reference solution

Optimal Combination of GNSS and Seismometer Observations

Example: 7.0 M_w earthquake Kumamoto, Japan, 2016



- Short-term precision of real-time GNSS displacements can reach level of millimeters
- Combination with strong-motion accelerometer observations: real-time (Kalman filter), near real-time (smoother)
- The result is a seismic broadband displacement and velocity waveform
- Fosters a fast and reliable earthquake response (e.g., finite fault inversion, early warning)

Optimal Combination of GNSS and Seismometer Observations

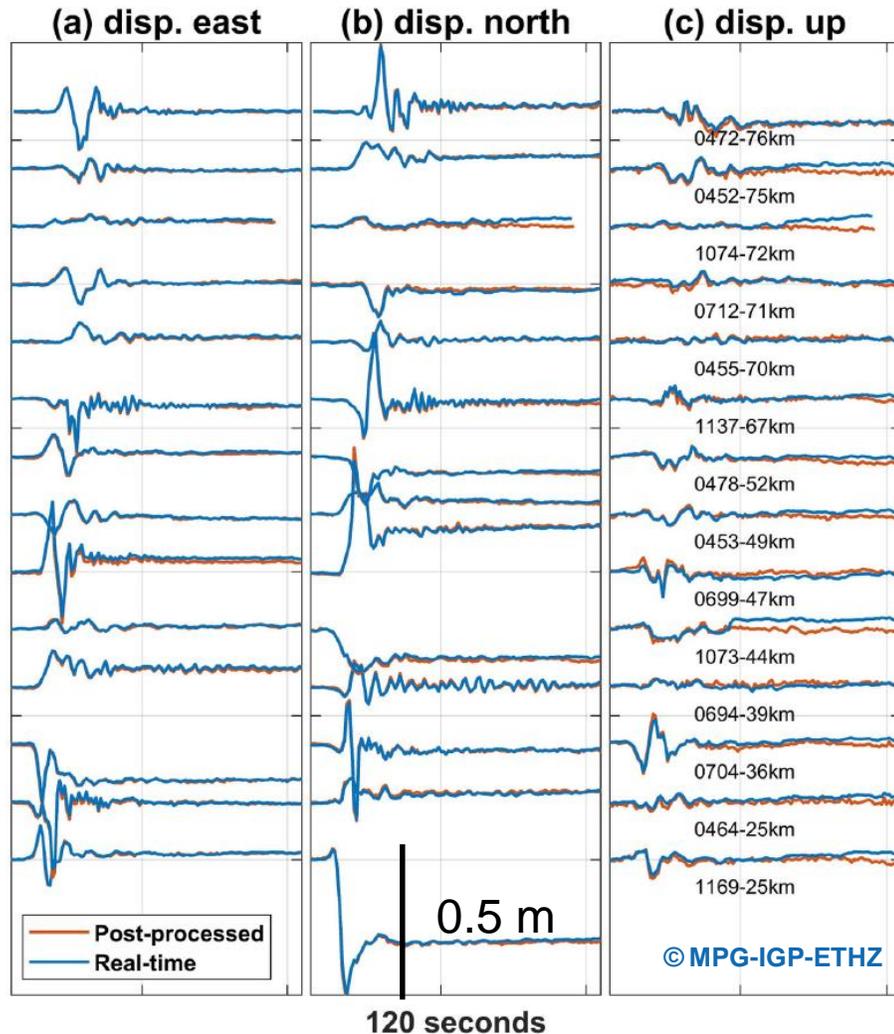
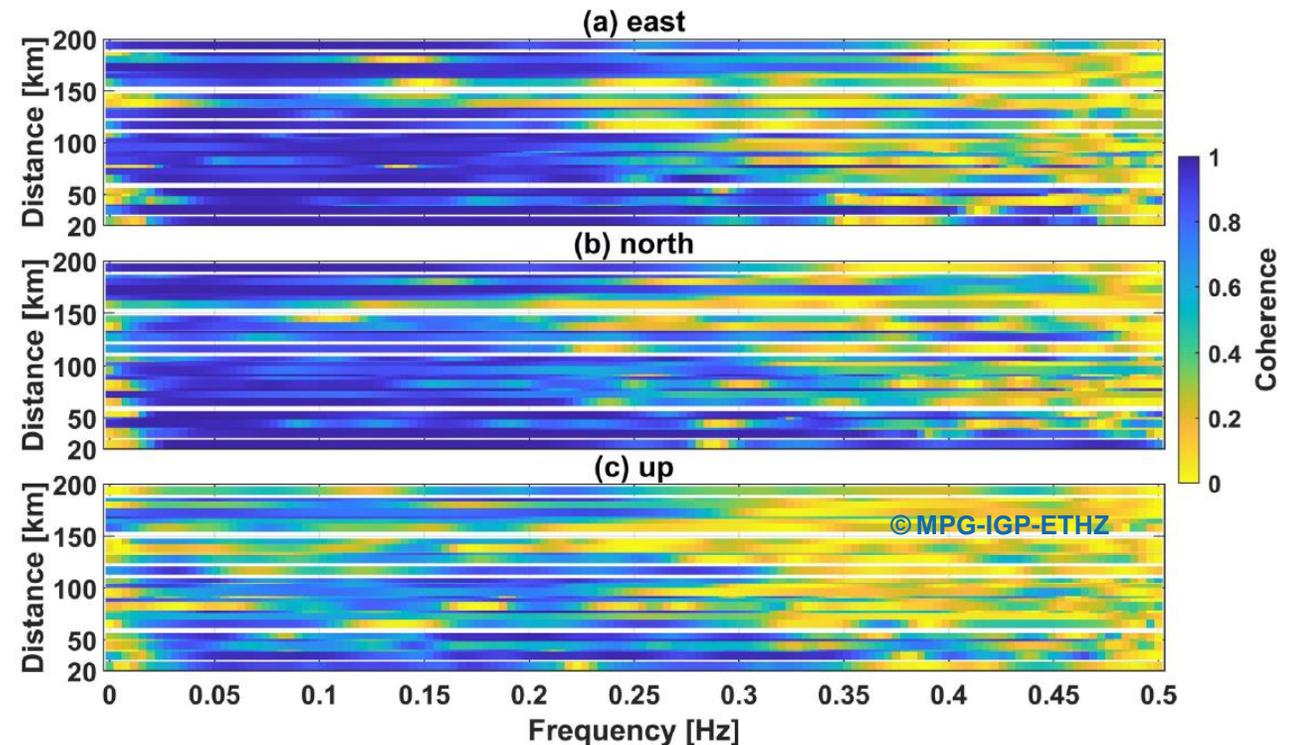


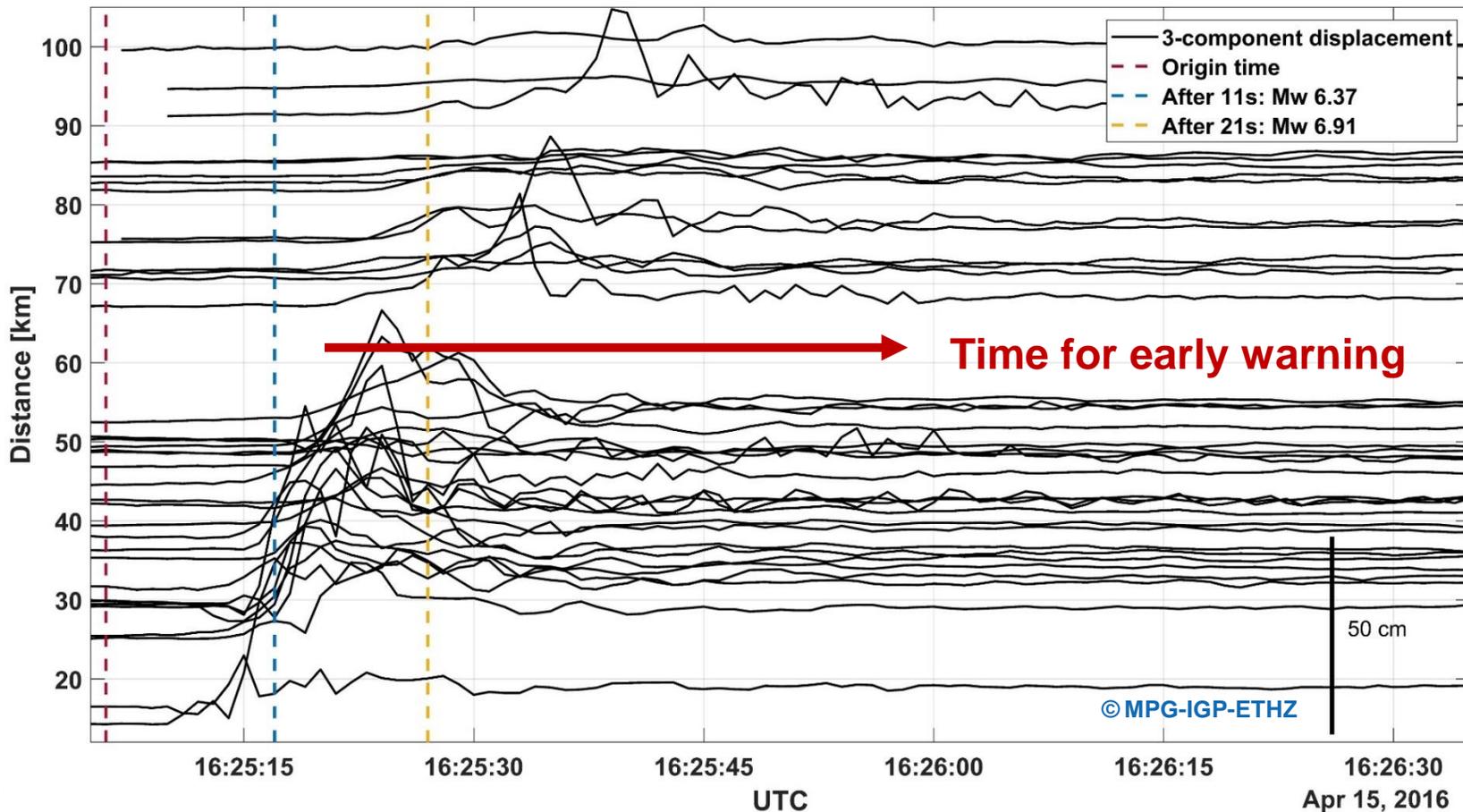
Figure (left) Kumamoto: comparison of postprocessed and real-time GNSS PPP for co-located stations up to 80 km

Figure (bottom) Kumamoto: coherence analysis of GNSS and seismometer displacements for co-located stations up to 200 km



GNSS and Earthquake Early Warning

- GNSS gives reliable estimates of the Magnitude by PGD (Peak Ground Displacements)

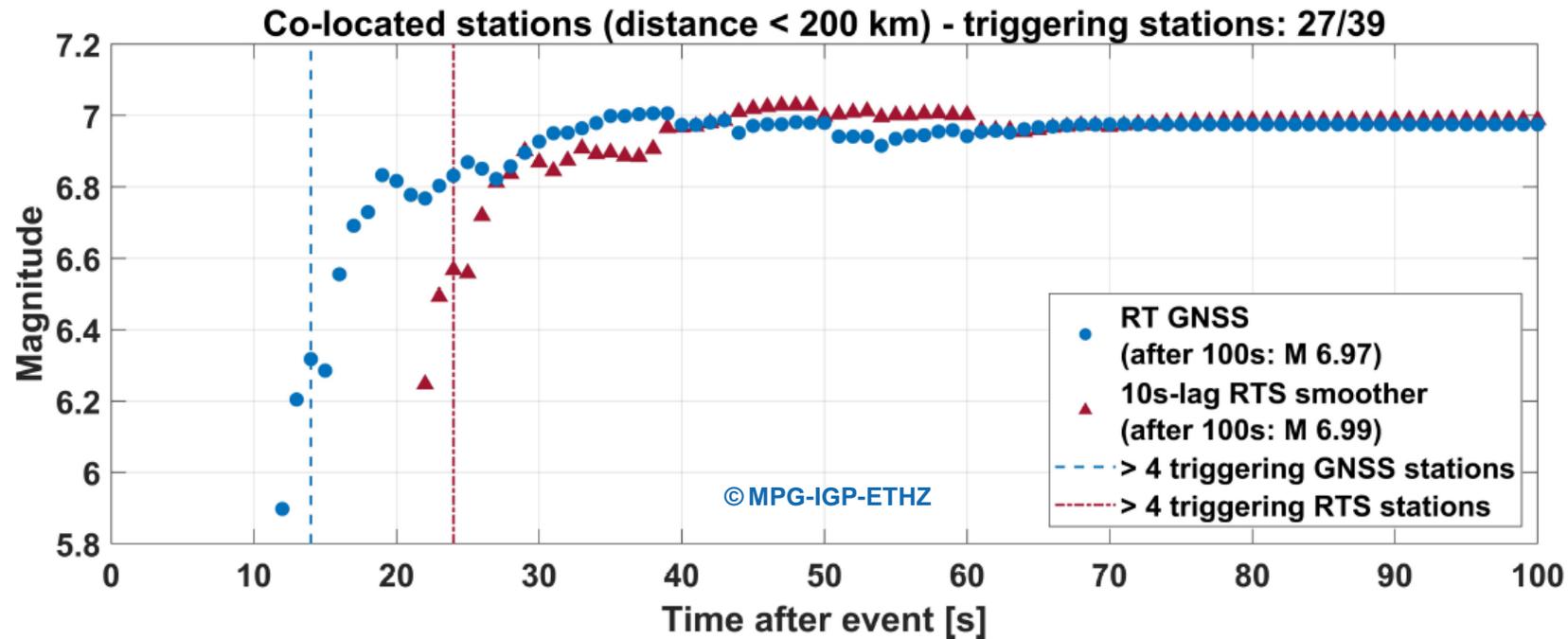


Melgar, Diego, et al. "Earthquake magnitude calculation without saturation from the scaling of peak ground displacement." *Geophysical Research Letters* 42.13 (2015)

Figure: Dahmen, N., Hohensinn R., Clinton J.F., «Comparison and Optimal Combination of GNSS and Seismometer Observations: a case study for the 2016 Kumamoto Earthquake», *Bulletin of the Seismological Society of America* (submitted)

GNSS and Earthquake Early Warning

- GNSS gives reliable estimates of the Magnitude by PGD

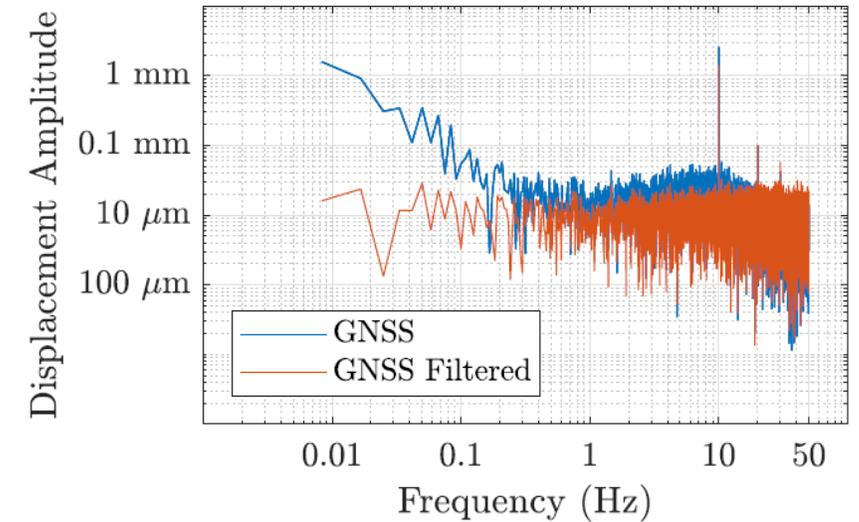
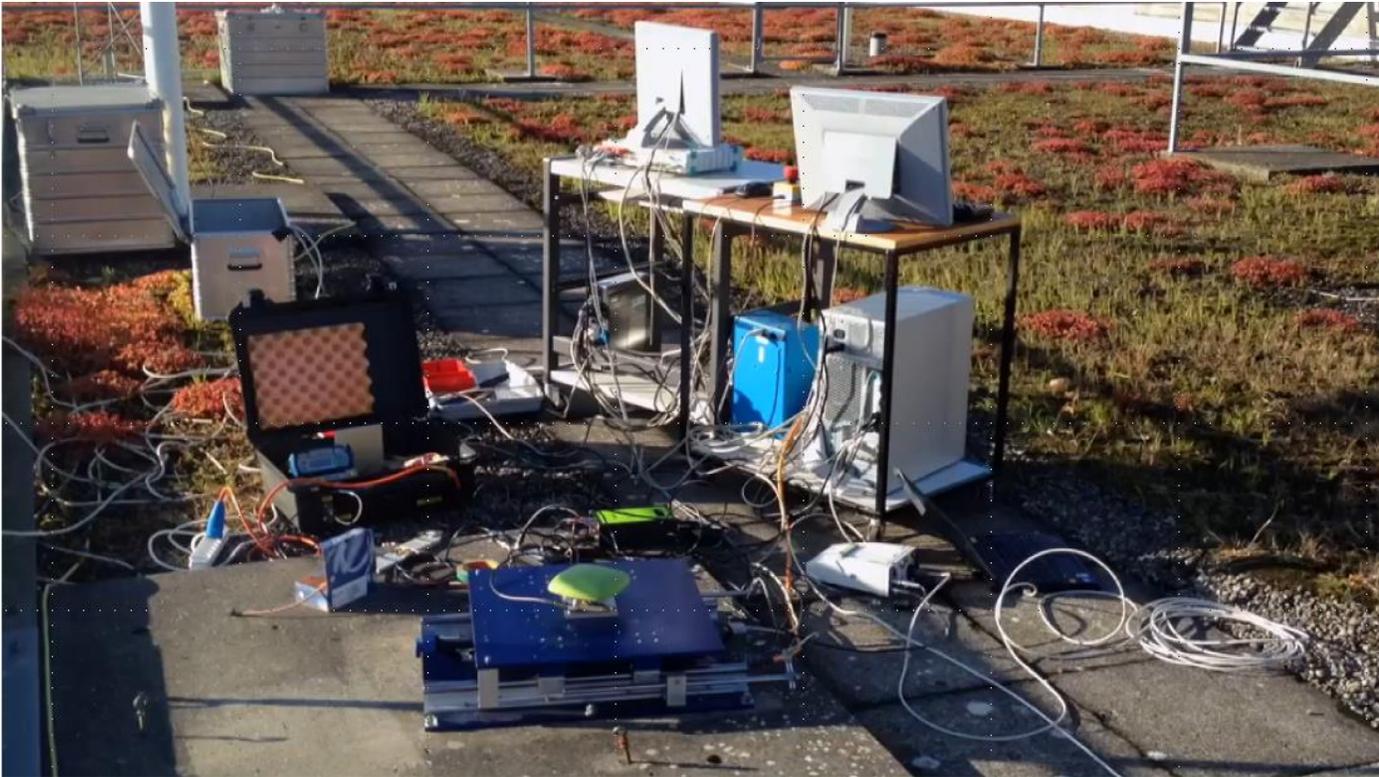


- Optimal choice of GNSS stations by statistical testing for significant displacements

Figure: Dahmen, N., Hohensinn R., Clinton J.F., «Comparison and Optimal Combination of GNSS and Seismometer Observations: a case study for the 2016 Kumamoto Earthquake», Bulletin of the Seismological Society of America (submitted)

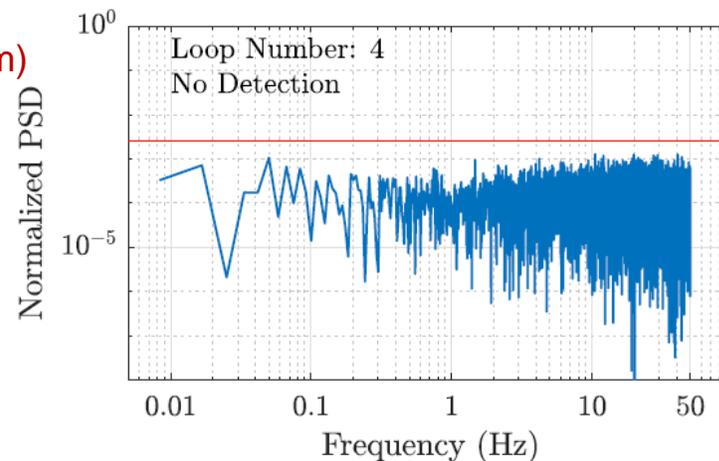
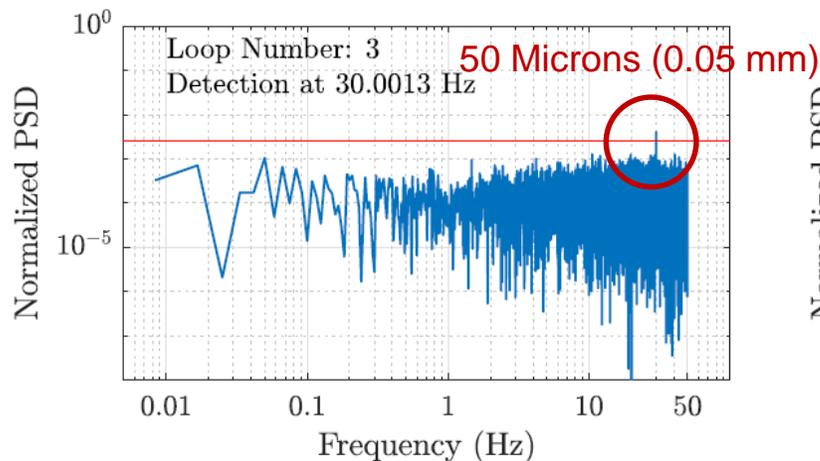
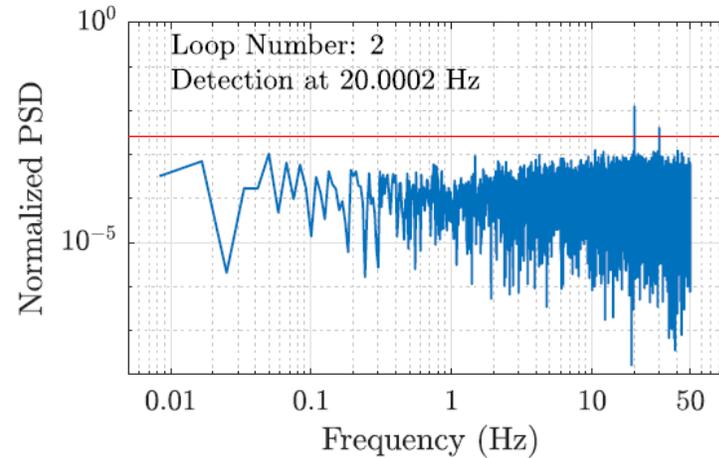
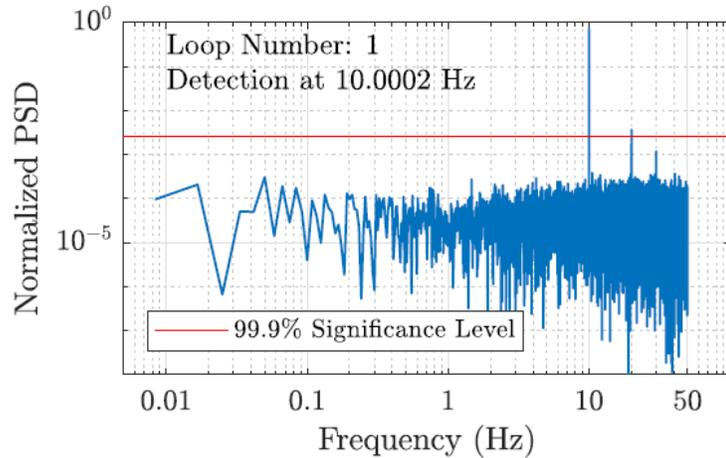
Vibration Detection with GNSS

- **Basis: High-rate (100 Hz) displacement time series (short baseline)**



For the detection of the smallest signals, error models have to be calibrated

Vibration Detection with GNSS



Workflow

1. Error model calibration (ARMA/ARIMA models)
2. Prewhitening
3. Vibration Detection (Fisher Test)
4. Optionally repeat procedure

Conclusions

- **GNSS can resolve ground motions down to millimeters in real-time**
- **Effects of colored GNSS noise should be accounted for**
- **Dense GNSS networks (spacing of few tens of kilometers, like GEONET in Japan) foster reliable Earthquake Early Warning**
- **Broadband seismogeodesy (including rotational sensors) further pushes rapid and reliable response to earthquakes**